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(54) **Single longitudinal mode semiconductor laser.**

(57) The semiconductor laser diode comprises a distributed Bragg reflector formed on a substrate. The reflector includes an optical waveguide sandwiched between first and second cladding regions formed over the substrate. The optical waveguide has a corrugated region extending within the optical waveguide in a direction parallel to the surface of the substrate. The thickness of the corrugated region varies in a prescribed period and the refractive index of the corrugated region differs from that of the optical waveguide. An optically active layer formed over the substrate is butt-jointed to the optical waveguide, and emits light beams when a current is injected into it. This single longitudinal mode semiconductor laser has high performance features. Its equivalent reflecting power is increased by so structuring the grating section that it is highly efficient in coupling the periodic structure and light.

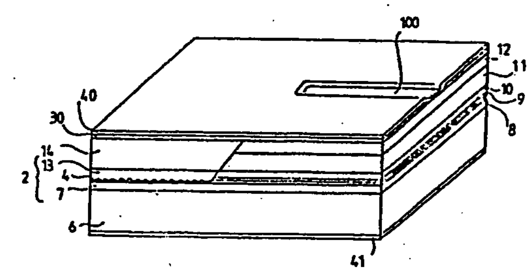

Fig. 4

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Croydon Printing Company Ltd.

Single Longitudinal Mode Semiconductor Laser

The present invention relates to a single longitudinal mode semiconductor laser suitable as a light source for optical fiber communication systems.

As the transmission loss of optical fibers has been so drastically reduced as to be no more than 0.2 to 0.5 dB/km in the 1.3 and 1.5 micron wavelength bands, it has become possible to realize an optical fiber communication system having a relaying distance of more than 100 km. In long-distance transmission, the transmissible relaying distance and capacity are limited not only by the transmission loss of optical fibers but also by wavelength dispersion. The effect of wavelength dispersion is remarkable in long-distance optical fiber transmission using the conventional Fabry Perot resonator type semiconductor lasers, which usually has a plurality of oscillating longitudinal modes. Therefore, realization of a long-distance large-capacity optical fiber communication system would require semiconductor lasers capable of oscillating in a single longitudinal mode even in high-speed modulation.

Such semiconductor lasers include the distributed feedback laser diode (DFB LD) with a built-in diffraction grating having a periodic structure and the distributed

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Bragg reflector laser diode (DBR LD). These semiconductor lasers, which can select the oscillation longitudinal mode, are still in the process of research and development, and only recently became capable of continuous operation at room temperature. There is a long way to go before they can be successfully applied to practical purposes because they are inferior to the conventional Fabry Perot oscillator type semiconductor laser in such basic performance features as oscillation threshold and differential quantum efficiency. The biggest reason for their inferiority consists in their lower equivalent reflecting power, which in turn results from the weak coupling between light and the periodic structure constituting the diffraction grating, resulting in a poor light diffraction efficiency. In a DBR LD, for instance, a low reflecting power in the diffraction grating section invites an increase in injection current required for laser oscillation.

Moreover, as the region in which the grating is formed has to be made as long as possible in order to increase the reflecting power in the diffraction grating section, the overall element length is inevitably extended to around 1 mm, and there are a number of other disadvantages in element performance and fabrication aspects.

Summary of the Invention

It is an object of the present invention to provide a

distributed Bragg reflector type single longitudinal mode semiconductor laser having high performance features, with its equivalent reflecting power increased by so structuring the grating section as to be highly efficient in coupling the periodic structure and light.

A semiconductor laser diode, in accordance with the present invention, comprises a distributed Bragg reflector formed on a substrate. The reflector includes an optical waveguide sandwiched between first and second cladding regions formed over the substrate, the optical waveguide having a corrugated region extending within the optical waveguide in a direction parallel to the surface of the substrate. The thickness of the corrugated region varies in a prescribed period and the refractive index of the corrugated region differs from that of the optical waveguide. An optically active layer formed over the substrate is butt-jointed to the optical waveguide, and emits light beams when a current is injected into it.

Brief Description of the Drawings

Other advantages and features of the present invention will be more apparent from the detailed description hereunder taken in conjunction with the accompanying drawings, wherein:

FIG. 1 shows, together with the field distribution in the waveguide, a longitudinal section of a distributed Bragg reflector of prior art;

FIG. 2 shows, together with the field distribution in the waveguide, a longitudinal section of a distributed Bragg reflector for use in the present invention;

FIG. 3 shows a longitudinal section of the basic structure of the distributed Bragg reflector according to the invention;

FIG. 4 shows an oblique view of a distributed Bragg reflector laser diode (DBR LD) constituting a first preferred embodiment of the invention;

FIGS. 5a to 5d show sectional views for describing the fabricating process of the semiconductor laser diode illustrated in FIG. 4;

FIG. 6 shows an oblique view of a semiconductor laser diode constituting a second preferred embodiment of the invention; and

FIG. 7 shows an oblique view of a semiconductor laser diode constituting a third preferred embodiment of the invention.

Detailed Description of the Preferred Embodiments

Before describing the preferred embodiments, the basic principle underlying the present invention will be explained.

FIG. 1 shows a sectional view of a diffraction grating constituting a distributed Bragg reflector of prior art structure, so composed that semiconductor layers 1 and 3 having refractive indices n_1 and n_3, respectively, sandwich

between them a semiconductor optical waveguide layer 2 having a refractive index n_2, which is greater than both n_1 and n_3. Over the top of the optical waveguide layer 2 there is formed a periodic structure having a period Λ and a depth d. Where the x axis is set in the direction of lamination, the y axis in a direction normal to the face of the figure within the semiconductor film face, and the z axis in a direction parallel to same, a light beam entering the optical waveguide 2 of the distributed Bragg reflector in the direction of the z axis from the lefthand side of the figure propagates confined within this optical waveguide layer 2 because the refractive index n_2 of this layer 2 is greater than those of the upper and lower layers. As the film thickness of the optical waveguide layer 2 varies in the period Λ, the effective refractive index $\bar{n}_2$ of the layer 2 also periodically varies in the direction of the z axis. Light beams of the Bragg wavelength λ_B, which equal $2\,m\Lambda\bar{n}_2$ (m: an integer), are greatly diffracted. Therefore, light beams of the Bragg wavelength, out of all the incoming beams, are distributively reflected while they propagate through the optical waveguide layer 2, and are returned to the side they came from. An element in which such a wavelength-selective Bragg reflector is provided as the semiconductor laser reflector instead of the usual cleaved face is the distributed Bragg reflector semiconductor laser. Semiconductor lasers having such a

structure have been described in the U.S. Patent Application Serial No. 447,553, filed on December 7, 1982, and Serial No. 541,211, filed on October 12, 1983, both by the present inventor.

The maximum value of the reflecting power R_B in this waveguide is given by the following equation:

$$R_{B,max} = \tanh^2 (KL)$$

where K is the coupling constant of corrugation and L, the length of the waveguide. Because the reflecting power $R_{B,max}$ rises with increases in K and L, performance improvements including reduction of the oscillation threshold of the semiconductor laser can be thereby achieved. However, merely increasing L while keeping K small would invite an increase of loss owing to the absorption of light during propagation through the optical waveguide 2 among other reasons. Therefore, the enlargement of K is vital to improving the performance features of the semiconductor laser.

K is given by the following equation:

$$K = A \int_{-\infty}^{\infty} \left\{\Delta \bar{n}(x)\right\}^2 \cdot \left\{\mathcal{E}_y(x)\right\}^2 \, dx$$

where $\mathcal{E}_y(x)$ is the electric field distribution of light beams in the y direction and $\Delta \bar{n}(x)$ is the variation of the effective refractive index.

The greater the depth d, the greater the effective refractive index variation. Thus, the greater the depth d

and the greater the electric field component of light beams in this region, the larger will be K.

In the prior art structure, where a periodic structure is formed on the upper (or lower) face of the optical waveguide layer 2, the electric field component of light beams is small in the periodically varying region of the refractive index, as is indicated by the electric field distribution of optical beams, which is determined by the geometric form in FIG. 1, and therefore it is difficult to obtain a large value for K.

FIG. 2 shows a sectional view of a distributed Bragg reflector to be used in the present invention. Substantially along the center line of an optical waveguide layer 2 there are periodically formed semiconductor layers 4 having a refractive index n_4 which is different from the refractive index n_2 of the optical waveguide layer 2 (it may be either greater or smaller than n_2). In this manner, the electric field component of light beams subjected to the periodic variations of the refractive index, as illustrated by the electric field distribution of light beams in FIB. 2, can be maximized, so that the value of K can be increased.

In the case where 60 to 90 percent of light beams are confined within the optical waveguide 2, the magnitude of the electric field of light beams in the central section of the optical waveguide layer 2 is from three to ten times greater than that of the electric field of light beams on

the upper or lower face of same. Accordingly, the structure of FIG. 2 can result in a K value 10 to 100 times greater than that of Fig. 1. Although, in practice the electric field distribution of light beams in the structure of FIG. 2 is somewhat deformed as the effective refractive index drops in the middle of the optical waveguide layer 2; K can be made evidently larger than in the structure of FIG. 1. Therefore, the reflecting power R_B can be enlarged, resulting in a remarkable improvement of the performance characteristics of the distributed Bragg reflector semiconductor laser.

FIG. 3 shows a sectional view of the basic composition of the distributed Bragg reflector semiconductor laser according to the present invention. The distributed Bragg reflector illustrated in FIG. 2 is shown on the lefthand side of figure 3 and an active layer 5, having a narrower forbidden band width than the optical waveguide layer 2, is butt-jointed to the optical waveguide layer 2 at a connection point 50. Like the optical waveguide layer 2, the active layer 5 is sandwiched between semiconductor layers 1 and 3, both having wide forbidden bands and small refractive indices. An end face 60 of the active layer 5 on the righthand side of the figure is a reflective face. If the semiconductor layers 1 and 3 are n and p types, respectively, there will be a double heterostructure in which a pn junction is formed at the active layer 5, so that

the injected carrier will be efficiently confined within the active layer 5 to emit light beams.

The light beams so emitted are guided within the active layer 5, and those proceeding toward the lefthand side of the figure go incident on the optical waveguide layer 2 of the reflected Bragg reflector via the connnection point 50. Out of the light beams incident on the distributed Bragg reflector, those having wavelengths corresponding to the Bragg wavelength are strongly diffracte and return to the active layer 5. Therefore, the distribute Bragg reflector, together with the reflector on the end face 60 of the active layer 5 on the righthand side of the figure constitutes a wavelength-selective resonator.

The distributed Bragg reflector semiconductor laser of this structure is characterized in that its distributed Bragg reflector can be given a high reflecting power and that the active layer 5 and the optical waveguide layer 2 are butt-jointed so that the light beam coupling efficiency can be more than 90 percent, resulting in a low oscillation threshold, as well as by a high differential quantum efficiency.

FIG. 4 shows an oblique view of the distributed Bragg reflector semiconductor laser, which is a first preferred embodiment of the present invention.

Its structure will be described below with reference to the fabrication procedure illustrated in FIGS. 5a to 5d.

InGaAsP layers and InP layers are used as semiconductor materials. A distributed Bragg reflector is structured utilizing the fact that the refractive indices of the InGaAsP layers (having a 1.15 micron composition in terms of the wavelength of the light emitted) are greater than that of InP. First, on an n-InP substrate 6 there are successively grown by liquid-phase epitaxy (LPE) a first optical waveguide layer 7 of n-InGaAsP (1.15 micron composition in terms of light wavelength, 0.3 micron thick), an n-InP layer 8 (0.1 micron thick), an active layer 9 of non-doped InGaAsP (1.3 micron composition in terms of light wavelength, 0.15 micron thick), a second optical waveguide layer 10 of p-InGaAsP (1.15 micron composition in terms of light wavelength, 0.2 micron thick), a first cladding layer 11 of p-InP (2 microns thick) and an electrode forming layer 12 of p-InGaAsp (1.2 micron composition in terms of light wavelength, 1 micron thick). The resultant wafer is illustrated in FIG. 5a. Then, as shown in FIG. 5b, the region on the lefthand side of the figure is etched, the rest being masked with an SiO_2 film 70, to expose the n-InP layer 8. At this step, the properties of sulfuric acid-based etching liquid and hydrochloric acid-based etching liquid can be effectively utilized to selectively etch InGaAsP semiconductor layers and InP semiconductor layers, respectively.

Next, a primary diffraction grating 80 having a period of 1980 Å is formed in the n-InP layer 8 by the conventional

holographic interference exposure method using He-Cd gas laser and etching. The result is illustrated in FIG. 5C. With the SiO_2 film 70 being used as growth inhibiting mask, a second round of LPE growth is achieved to grow a third optical waveguide layer 13 of p-InGaAsP (1.15 micron composition in terms of light wavelength, 0.4 micron thick) and a second cladding layer 14 of p-InP (3 microns thick). The resultant state is shown in FIG. 5d. After removing the SiO_2 film 70 and newly forming a SiO_2 insulating film 30 all over, a 10 micron current injecting stripe region 100 is opened on the electrode forming layer 12 for injecting an electric current, and then a p-side metal electrode 40 of Au-Zn is formed. Next, after the side of the n-InP subtrate 1 is ground until the overall thickness is reduced to about 100 microns, an n-side electrode 41 of Au-Ge-Ni is formed, cleaved and cut out to obtain an element having the structure illustrated in FIG. 4.

In this structure, the optical waveguide 2, including the first optical waveguide layer 7 of InGaAsP, the third optical waveguide layer 13 and the corrugated layer 4 of InP sandwiched between the two optical waveguide layers, constitutes a distributed Bragg reflector, placed between the InP substrate and the second cladding layer. Meanwhile, the optical waveguide in the light emitting region adjoining this distributed Bragg reflector includes the first optical waveguide layer 7, the third optical waveguide

layer 10, the active layer 9 sandwiched between the two optical waveguide layers, and the InP layer 8 having the same composition as the corrugated layer 4. The waveguide in the light emitting region is enclosed by the substrate 6 having a low refractive index and the first cladding layer 11.

When the region containing the active layer 9 and the distributed Bragg reflector section, respectively, are 300 microns and 500 microns long, the element has an oscillation threshold of 150 mA and a differential quantum efficiency of 15 percent on one side, both approximately.

Its oscillating wavelength is around 1.30 microns, and a single longitudinal mode is maintained in the injected current region of up to about 2.5 times the oscillation threshold. The oscillating wavelength, depending on the heat sink temperature, varies at 1.0 Å/°C. This is a quantity corresponding to the temperature-dependent variation of the refractive index, and is substantially equal to previously reported values. The satisfactory oscillation threshold and differential quantum efficiency are attributable to the high reflecting power in the distributed Bragg reflector section.

FIG. 6 shows an oblique view of a second preferred embodiment of the present invention.

The structure of its distributed Bragg reflector section is the same as in the first embodiment illustrated

in FIG. 4. This embodiment differs from the first in that its active layer 9 is produced after the formation of the distributed Bragg reflector section. Thus, after a first optical waveguide layer 7 of n-InGaAsP (1.15 micron composition in terms of light wavelength, 0.2 micron thick) and an n-InP layer 8 (0.1 micron thick) are grown on an n-InP substrate 6 by the first round of LPE growth, a diffraction grating 80 having a period of 1980 Å is formed in the n-InP layer 8.

In the second round of LPE growth, a third optical waveguide layer 13 of p-InGaAsP (1.15 micron composition in terms of light wavelength, 0.2 micron thick) and a second cladding layer 14 of p-InP (3 microns thick) are laminated. Then, as in the case of the first embodiment, partial etching to the-InGaAsP waveguide layer 7 is achieved by the use of hydrochloric acid-based and sulfuric acid-based selective etching liquids. In the third round of LPE growth, by the use of an SiO_2 growth inhibiting mask over the third cladding layer 14 of p-InP, there are formed only in the etched part a buffer layer 15 of n-InP (0.3 micron thick), an active layer 9 of non-doped InGaAsP (1.3 micron composition in terms of light wavelength, 0.15 micron thick), a cladding layer 11 of p-Inp (2.2 microns thick) and an electrode forming layer 12 of p-InGaAsP (1.2 micron composition in terms of light wavelength, 1 micron thick). The LPE growth procedure ends here, and the remaining

electrode forming step is the same as in the case of the first embodiment.

In this second embodiment, the first optical waveguide layer 7, the corrugated layer 8 and the third optical waveguide layer 13 constitute an optical waveguide, and provide a distributed Bragg reflector. Adjoining the corrugated layer there is arranged the optical active layer 9.

An element of this structure has substantially the same performance characteristics as the first embodiment, its oscillation threshold being 150 mA and differential quantum efficiency of about 15 percent on one side. Its oscillating wavelength is in a single longitudinal mode in the vicinity of 1.30 microns.

In the first and second embodiments having gain waveguide-type semiconductor laser structures, no waveguide is formed in a plane normal to the laminating direction in the distributed Bragg reflector section. Accordingly, only a small proportion of the light beams which are incident on the distributed Bragg reflector return to the light emitting region of the active layer 9.

If a waveguide connected to the light emitting region of the active layer 9 is formed in the distributed Bragg reflector section as well, their performance features will be further improved.

FIG. 7 shows an oblique view of a third preferred embodiment of the present invention, having a buried

heterostructure formed on the basis of the structure of the first embodiment. After removing the electrode forming layer 12 of p-InGaAsP from the structure of the first embodiment illustrated in FIG. 5d and producing a multi-layer wafer in which the cladding layer 11 of p-InP and the second cladding layer 14 of p-InP are 1 micron thick each, two parallel grooves 90 and 91 are so formed in the direction of 110 that the grooves are about 7 microns wide each and a mesa stripe 92, formed between the two grooves 90 and 91, is about 2 microns wide. On this mesa substrate, a current blocking layer 16 of p-InP (about 0.5 micron thick in its flat part) and a current confining layer 17 of n-InP (about 0.5 micron thick in its flat part) are so grown that they may not grow over the mesa stripe 92. Then there are grown, covering the whole structure, an embedding layer 18 of p-InP (1.5 microns thick in its flat part) and an electrode forming layer 12 of p-InGaAsP (1.2 micron composition in terms of light wavelength, 1 micron thick in its flat part) to form a wafer of buried structure (For further details on a buried structure, reference may be made to the U.S. Patent Applications Serial No. 447,553 and Serial No. 541,211.). Whereas the electrode forming step is the same as that for the first embodiment, an SiO_2 insulating film 30 is required only over the distributed Bragg reflector section because there is a current confining structure within. In this

structure, there is formed, in the mesa stripe 92, a rectangular waveguide extending from the light emitting section including the active layer 9 to the distributed Bragg reflector section. Therefore, most of the light beams diffracted by the distributed Bragg reflector section are returned to the waveguide of the active layer 9. When the region of the active layer 9 and the distributed Bragg reflector are 300 microns and 500 microns long, respectively, both the oscillation threshold and differential quantum efficiency of the element will be satisfactory, the former being 30 mA and the latter 20 percent on one side. Its oscillating wavelength is around 1.30 microns, and has a single mode where the injected current is no more than around three times the threshold. The variation of the oscillating wavelength dependent on the temperature variation of the heat sink is about 1 Å/°C, i.e. it is substantially equal to those of the first and second embodiments.

The buried structure can be applied equally effectively to the structure of the second embodiment.

Although InP substrates are used in the foregoing embodiments, it also is possible to obtain embodiments of the present invention using an $Al_x Ga_{1-x} As$-based material on a GaAs substrate or an InGaAsP-based material similarly on a GaAs substrate.

Finally to sum up the features of the invention, it offers the advantage of forming a distributed Bragg reflector having

a high diffractive efficiency by arranging the periodic variation of the refractive index approximately in the middle of the waveguide; this results in low oscillation threshold and high differential quantum efficiency.

What is claimed is:

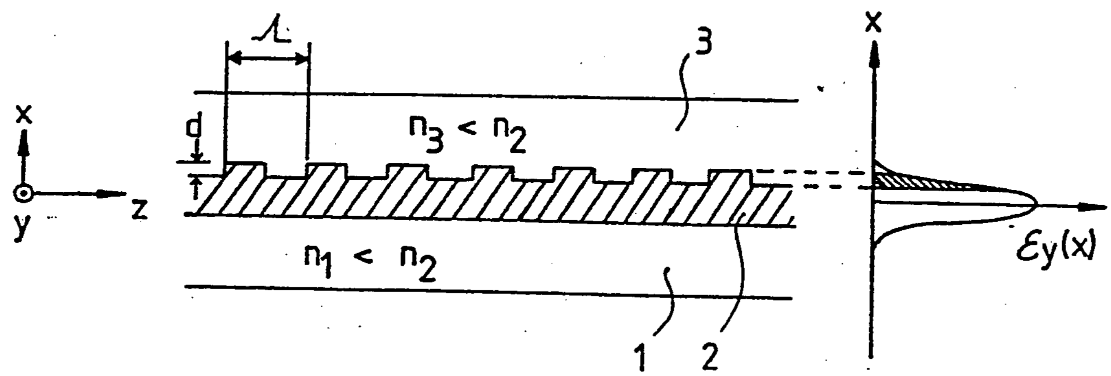
A semiconductor laser diode comprising:

a substrate;

an optical waveguide sandwiched between first and second cladding regions formed over the substrate, the optical waveguide having a corrugated region extending within the optical waveguide in a direction parallel to the surface of the substrate, the thickness of the corrugated region varying in a prescribed period and the refractive index of the corrugated region differing from that of said optical waveguide; and

an optically active layer which, butt-jointed to said optical waveguide and formed over said substrate, emits light beams when a current is injected into it.

Fig. 1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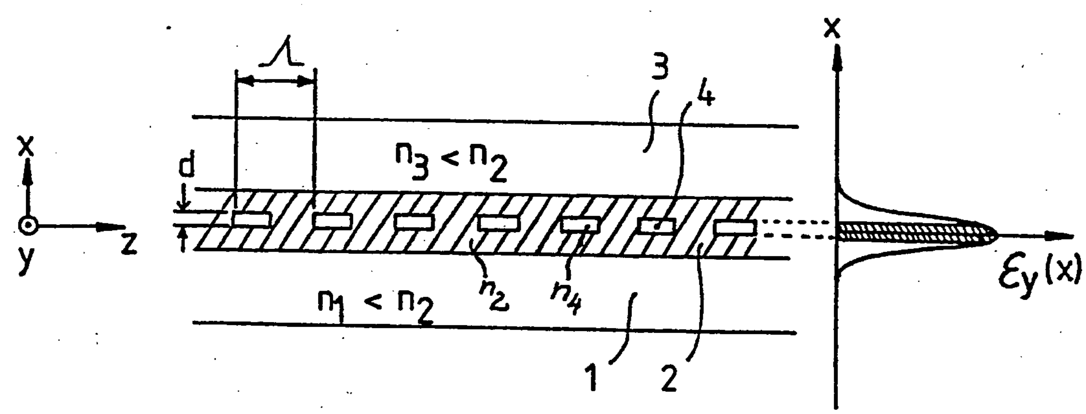
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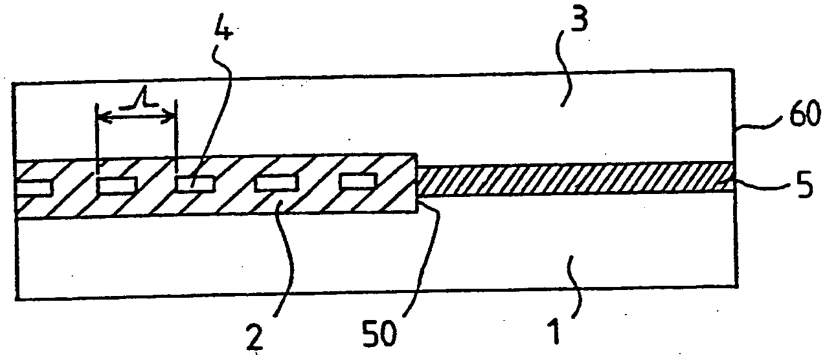
Fig. 2

Fig. 3



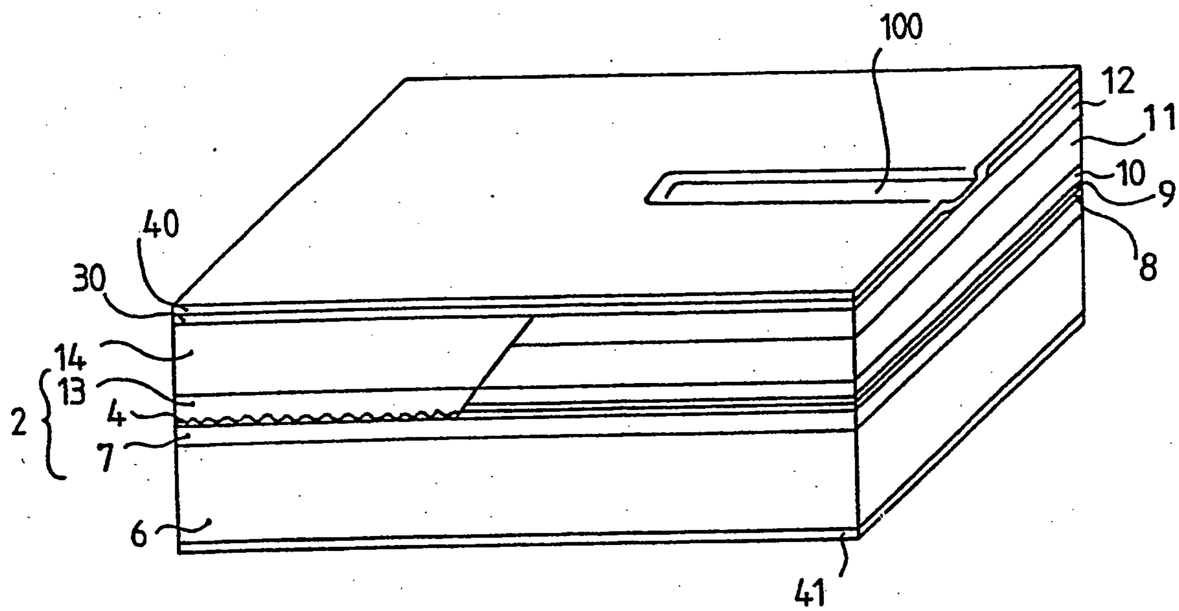


Fig. 4

a

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c

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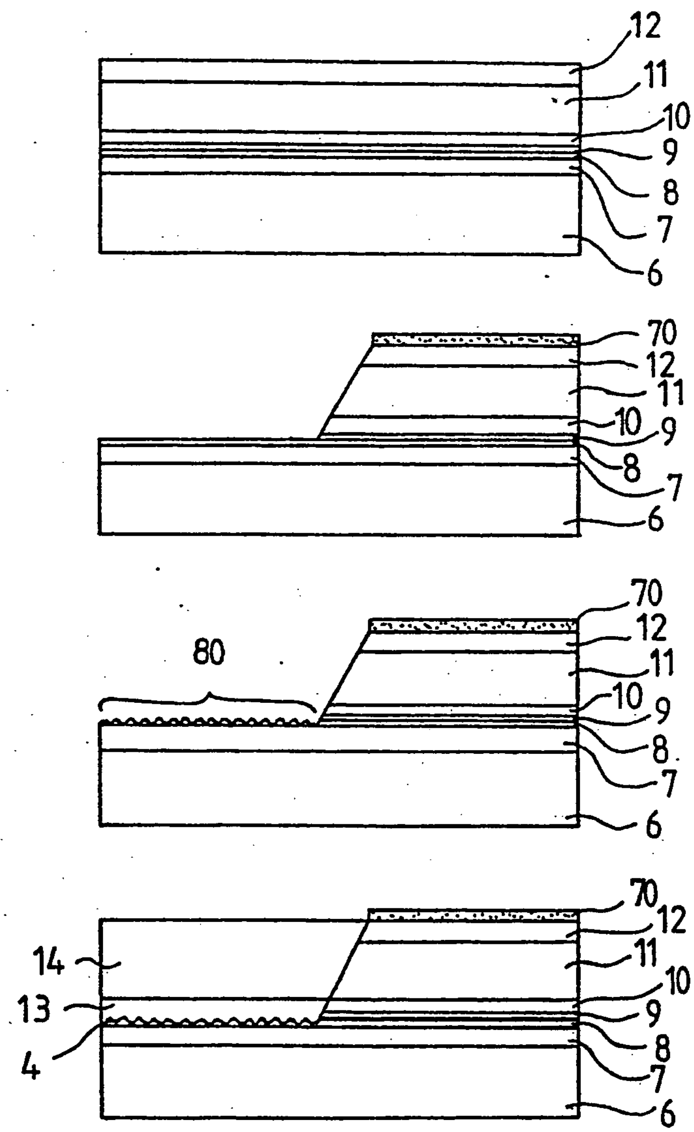
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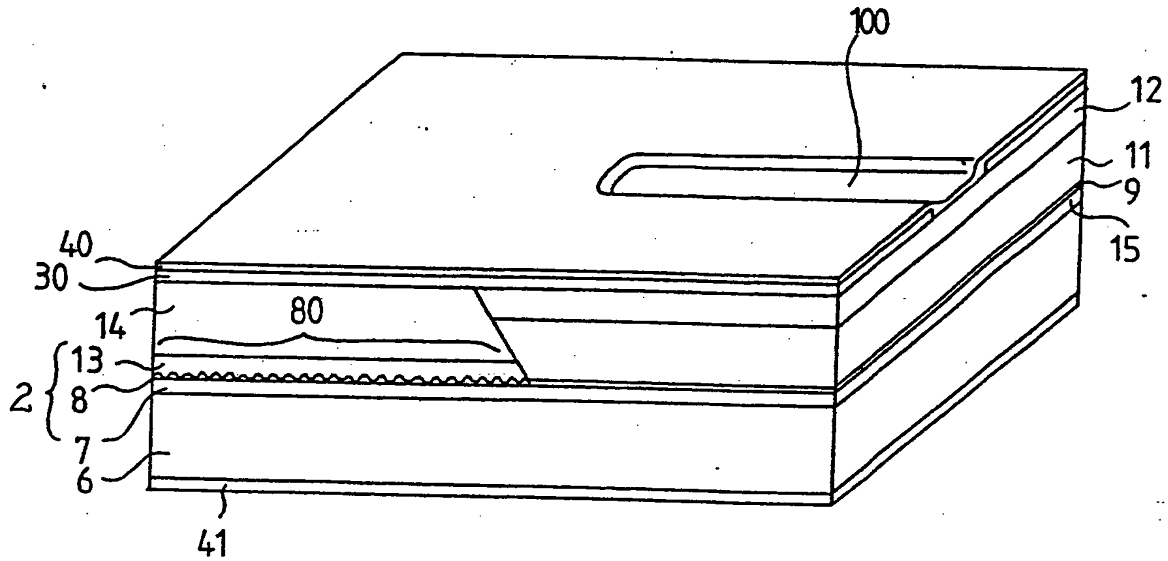
Fig. 5

Fig. 6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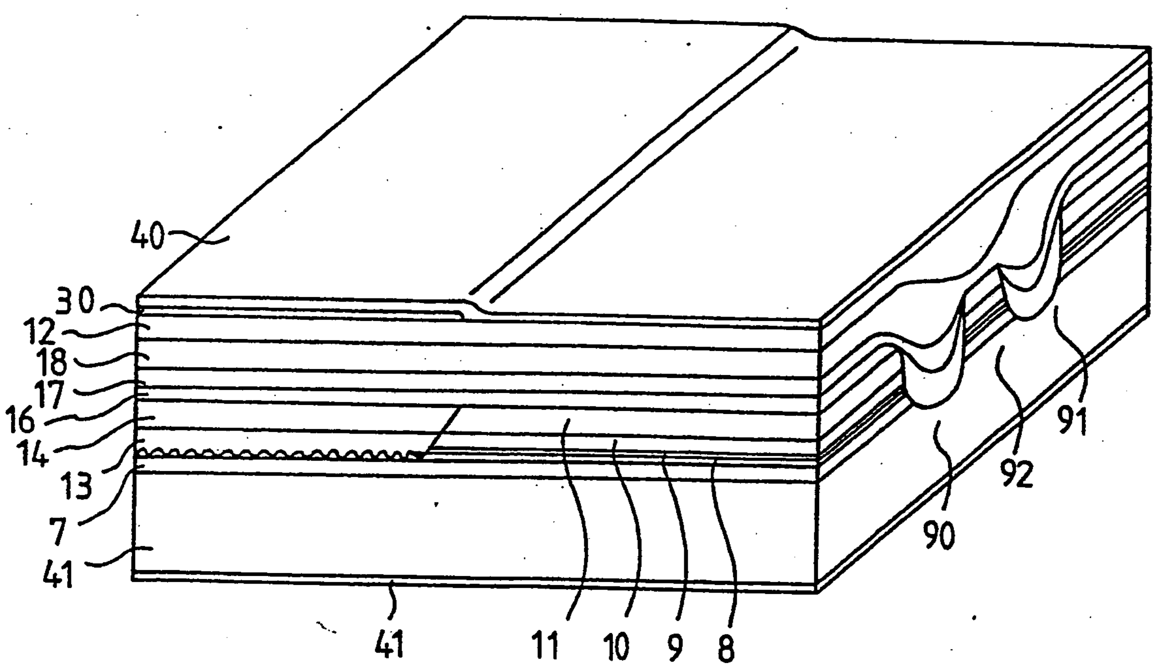
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Fig. 7